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ABSTRACT

A PROTOCOL FOR CONDUCTING CLOSED-CIRCUIT ANESTHESIA

David M. Huether, B.A., B.S.N.

This study developed a protocol for the conduct of closed-circuit anesthesia. The problem is that anesthetists are unfamiliar with this anesthetic technique. Even a very promising system for delivery of general anesthesia, such as closed-circuit anesthesia, cannot be employed if there is a lack of understanding of its theory and practice. The purpose of this study was to describe the theoretical background for closed-circuit anesthesia, and to explain how this technique is practiced, in order to increase its acceptance by anesthesia providers.

The method employed for investigating this topic was entirely library research, anesthesia journals and texts. Tables and an illustration were used to demonstrate closed-circuit anesthesia practice and a protocol for delivering closed-circuit was developed. No original data were collected.

It was found that uptake of anesthetic is proportional to the square root of time. This allows doses of anesthetic to be calculated and injected precisely at ever increasing time intervals in order to give the patient enough anesthetic to conduct general surgery. The additional equipment needed to conduct closed-circuit anesthesia includes a low-flow capable

cont'd

anesthetic machine, polyethylene tubing, Baralyme absorber, an oxygen meter and a syringe for injecting liquid anesthetic.

Closed-circuit anesthesia was found to have several advantages over semi-closed high flow systems. It is less wasteful of expensive anesthetic, maintains a patient's temperature and is less polluting of the atmosphere and of the operating room suite. Because closed-circuit anesthesia is a practical alternative to high-flow systems, it is recommended that closed-circuit techniques be studied and adopted by anesthetists. Closed-circuit anesthesia can be used on any case where high flow systems are currently employed. It is further recommended that the quality of anesthesia equipment and machines be improved to accomodate the demands of closed-circuit anesthesia.

A PROTOCOL FOR CONDUCTING

CLOSED-CIRCUIT ANESTHESIA

by

David M. Huether, B.A., B.S.N.

A Research Presentation Paper
submitted in partial fulfillment
of the requirement for the degree of
Master of Science in Nurse Anesthesia

SAINT MARY'S COLLEGE

August, 1985

TABLE OF CONTENTS

Figure

Page

Chapter 1

INTRODUCTION

Closed-circuit anesthesia (CCA) is a technique characterized by closing the pop-off valve on a semi-closed circuit system and delivering oxygen and anesthetic agents within its confines. Anesthetic gases are carried into the respiratory tract completely by the fresh gas inflow and rebreathed gases. The respiratory tract and the reservoir are closed to the atmosphere on both inspiration and expiration. Rebreathing of exhaled gases occurs, except for carbon dioxide which is absorbed.

In the first years of this century, students of anesthesia experimented with CCA in an attempt to quantify the delivery and economize the use of very expensive anesthetic drugs. Dr. Ralph Waters published his work on the safe use of CCA in the 1920's, and the technique was widely used in the cyclopropane era (Waters:1926:160).

Closed circuit techniques were pushed into obscurity with the development of potent non-explosive agents and vaporizers that did not produce a precise output at low-flow rates (O'Leary:1971:7). Developments in the practice of CCA have occured in the 1920's. Now with the availability of better equipment and an accurate uptake and distribution model, the modern use of CCA makes it possible to administer anesthetic gases in a quantitative manner (Lowe and Ernst:1981:28).

The investigation into CCA was completed by an examination of current literature. This literature provided the investigator with the information necessary to describe theory, identify advantages, construct a

practical methodology, calculate the appropriate dosages, and discuss problems associated with CCA.

Statement of the Problem

The problem is a lack of familiarity on the part of anesthetists with CCA. A suitable and adequate anesthesia technique such as CCA cannot be employed if there is a lack of understanding of its theory and practice. Increased interest in CCA has taken place in the last decade. However, increased interest has not resulted in a corresponding advance in its actual practice. Closed-circuit anesthesia offers distinct advantages over semi-closed high flow systems. These advantages include pollution reduction, cost reduction, temperature and humidity maintenance without cumbersome equipment and enhanced monitoring capability (Millman:1978:443). Thus, closed-circuit anesthesia deserves a wider practice and consideration.

Purpose of the Investigation

The purpose of the investigation is to aquaint readers with concepts of CCA, describe and convince readers of its merit, thereby encouraging the practice of CCA. This investigation led to the development of a protocol for the practice of CCA that will hopefully improve anesthesia delivery and expand the repertoire of practicing anesthetists.

Chapter 2

BACKGROUND AND SIGNIFICANCE

In order to understand and be able to practice CCA, the practitioner ought to be familiar with anesthesia circuits, advantages and disadvantages, basic theory and the necessary calculations. These topics will be reviewed in this section of the investigation.

Circuit Types for Delivery of Anesthetic Gases

The nature of the following circuits was described by Kofke and Laffa in a book by Lebowitz et.al. (1982:464). In an open circuit, anesthetic gases are carried into the respiratory tract with atmospheric air. Since the respiratory tract is open to air at all times, there is no rebreathing of exhaled gases. This circuit was commonly employed for open-drop ether anesthesia.

Semi-open circuits allow anesthetic gases to be carried into the respiratory tract by fresh gas in-flow, and may be mixed with air. The respiratory tract is open to air at all times, except that a reservoir is placed in the circuit. The Mapelson circuit is considered semi-open.

Semi-closed circuits, a third type, are popularly employed today. The anesthetic gases are carried into the respiratory tract by fresh gas in-flow. The respiratory tract and reservoir are closed to the atmosphere on inspiration but open to it on expiration. Carbon dioxide is absorbed.

With closed-circuit, anesthetic gases are carried into the respiratory

tract by fresh gas in-flow and rebreathed gases. The respiratory tract and reservoir are closed to the atmosphere on both inspiration and expiration. Rebreathing of all gases except carbon dioxide, which is absorbed,occurs.

Advantages of Closed-Circuit Anesthesia

In 1926 Dr. Ralph Waters (1926:160) described his innovations in CCA delivery and cited advantages that are relevant today. Heat and moisture are not wasted with each exhalation. The cost of agents is greatly reduced, thus eliminating expense as a serious consideration. Closed-circuit anesthesia protects the surgical team from the cumulative effects of anesthetic drugs. Opportunity is provided for the anesthetist to observe how various drugs affect metabolism. Consumption of oxygen and anesthetic agents are easily charted in ml/minute. Learning CCA requires that the anesthetist master principles of uptake, distribution and signs of anesthetic depth.

Economy is frequently mentioned in anesthetic practice as a very desirable goal. First of all, CCA eliminates the need for very expensive vaporizers. Closed circuit anesthesia can easily be demonstrated to conserve very expensive agents such as isoflurane. One ml of liquid isoflurane costs 53 cents. In a semi-closed system at four liter fresh gas flows, at 1.25%, 15 ml of isoflurane is vaporized per hour at a cost of $7.95. Closed circuit consumption for that same person for that initial hour would use about 8 millileters of isoflurane at a cost of $4.24. Furthermore, CCA uptake decreases dramatically with time, reducing cost further. The same cost reductions apply to the carrier gases nitrous oxide and oxygen. The only costs that would increase, would be for carbon dioxide absorbing

material which is used up at a greater rate than with high-flow systems.

Several thousand dollars were saved annually because of the low consumption of anesthetic gases made possible by CCA at the University of Chicago (Mostert:1980:395). A study in 1977 calculated that as much as 80 million dollars worth of anesthetic gases exited pop-off valves per year in the United States (Herscher:1977:29). Several studies have indicated that with the advent of better but more expensive agents such as isoflurane, individual departments of anesthesia could see the savings of thousands of dollars with implementation of CCA (Cohen:1978:113).

The gases delivered from anesthesia machines are water free. An intubated patient is functionally deprived of his nose, turbinates and cilia. The lining of the trachea can be easily injured by this dry air (Chalon: 1972:338). These dry gases must be immediately heated to body temperature and saturated, resulting in dehydration and loss of cilary action. This evaporative loss from the tracheobronchial tree in addition to heat loss from the patient can be significant. In fact, when the fresh gas flows are 5 liters per minute, tissue damage results if the surgery lasts more than one hour (Chalon:1972:338).

This exposure to unhumidified gases can be minimized with the use of CCA because of the humidified gases that are rebreathed. Circuit humidity in CCA is maintained at 92-100% throughout the anesthetic (Lin:1980:354-361). Numerous methods for humidifying the high gas flows of a semi-closed system have required bulky apparatus with their own additional risks to the patient (Spaepen:1978:191; Klein:1974:225).

Closed-circuit anesthesia is the best remedy for operating room pollution with potent xenobiotics, and its use can be justified on that basis alone (Lin:1980:354-361). Scavenging systems are not as essential, since

CCA keeps anesthetic gases contained within the circuit (Bushman et.al. 1977: 575). A dramatic decrease in operating suite pollution also decreases the release of fluorocarbons into our atmosphere's ozone layer. Anesthetics have been calculated to account for as much as .5% of atmospheric halogen pollution (Millman:1978:443). The depletion of our atmospheres ozone layer by fluorocarbons has been theorized to cause increased cancer and global warming (Newsweek 1985, June:64:23). Thus, an additional economic benefit of reducing waste gases is attained by reducing the need for government surveillance in this area.

Closed-circuit anesthesia, because of its nature provides the opportunity to measure or calculate some very important functions such as oxygen consumption, early detection of leaks, depth of anesthesia and cardiac output (Lowe and Ernst:1981:16). The total ventilatory volume of a closed system includes the patient's functional residual capacity (FRC) and the volume of the circuit. Since this amount is constant, any changes in uptake will be readily apparent in the girth of the reservoir bag. Another advantage of CCA, therefore, is that without invasive monitoring, early signs of metabolic disturbances can be detected. Examples of easily monitored situations include clamping of major arteries, use of tourniquets, shock, low cardiac output states and hyperpyrexia.

Any anesthetized patient can have a metabolic disturbance such as acidosis that can go unrecognized for several minutes. In a semi-closed system, deterioration may continue past the patients ability to compensate. Closed-circuit anesthesia can provide a minute by minute monitor of a patient's metabolic status.

"The ability to monitor oxygen consumption out-weighs all other considerations in favoring the use of CCA" (Lowe and Ernst: 1981:142)

Closed-circuit anesthesia is accurate at any altitude. James and White (1984:1097) reviewed the effects of altitude upon high-flow semi-closed anesthetic delivery and found the minimum alveolar concentration concept inadequate. Baumgarten (1985:843) in a letter to the editor, stated that because the density of liquid anesthetic is independent of ambient pressure, liquid agent can be injected into a closed-circuit without concentration difficulties. Uptake of anesthetic in a closed-circuit will therefore be unaffected by delivering a general anesthetic in such locations as Mt. Everest or Death Valley.

Disadvantages of Closed-Circuit Anesthesia

Closed-circuit anesthesia requires some special equipment such as an oxygen monitor, and a leak-free and low-flow capable anesthetic machine. Because of CCA's demand for a leak-proof system and accurate oxygen monitors, it will place heavier demands on the maintenance of equipment. It is possible to give a hypoxic mixture with any anesthetic technique, and CCA is no exception. To prevent this very undesirable situation requires the constant vigilance of the anesthetist and a reliable oxygen monitor that has been checked and calibrated.

Nitrogen and other gases can accumulate in closed-circuits. Therefore, CCA requires that each patient be denitrogenated prior to induction. That is, the patient should breath 100% oxygen at high flows for two to five minutes prior to the induction of anesthesia. Since most

nitrogen resides in the functional residual capacity and highly perfused organs, it can quickly be replaced by oxygen. Nitrogen can still accumulate in the circuit, since body stores still contain about one liter. However, with a circuit volume of ten liters, the most nitrogen can account for with proper denitrogenation is 10% (Lowe and Ernst:1981:12; Morita:1985:345).

Other gases that could accumulate within the closed circuit include carbon monoxide, methane, acetone and hydrogen. In a study by Morita et.al. (1985:345), they concluded that any volatile compound could wash out from body stores and accumulate within the closed circuit. In extreme cases, these gases, especially if the patient had consumed alcohol, could reach flammable levels. Carbon monoxide, a natural by-product of hemoglobin degradation can also accumulate, but at insignificant levels. Therefore, they recommended that the closed-circuit be flushed with fresh gases every one to three hours.

The Application of Basic Anesthesia Concepts to Closed-Circuit Anesthesia

Minimum alveolar concentration is defined as the minimum alveolar concentration required to prevent movement in 50% of patients exposed to abdominal incision. Clinical anesthesia is that point where 95% of patients do not move in response to surgical stimulas and this occurs at 1.3 MAC (de Jong:1975:384). One and three-tenths MAC has been used in this paper as a starting point in approximating doses for CCA. Minimum alveolar concentration can be related to specific alveolar partial pressures and can be expressed in units of volume per cent, fractional atmospheres or torr. These values represent equivalent doses of the popular anesthetics.

The MAC values of various agents are additive, thus an equivalent

depth of anesthesia could be attained with 1.3 MAC of isoflurane or .65 MAC of isoflurane and .65 MAC of nitrous oxide. As an alveolar concentration, MAC is expressed as the volume (ml) of vapor per 100 ml. Therefore, an alveolar anesthetic concentration (CA) can be considered a multiple of a fraction of MAC. The CA can be expressed in ml of gas: CA = F(fraction) x MAC = ml of vapor/dl (Lowe and Ernst: 1981:28).

Lowe and Ernst (1981:28) discussed partition coeffients (L) in their book. Even if the alveolar and arterial anesthetic partial pressures are identical, the anesthetic concentrations can be different. These differences are related to the way anesthetics interact with the different constituents of the blood such as water, lipid and protein. These factors will determine an anesthetic agent's solubility. The solubility of a gas in a fluid is defined as the ratio of vapor concentration in the liquid phase to the concentration in the gas phase at equilibrium. This is called the blood:gas partition coefficient (L B/G) or Ostwald solubility coefficient (See Appendix A, Table 5).

The partition coefficient is important because it provides information about the speed of uptake of anesthetics. The concentration of anesthetic within the lung also affects speed of uptake. For example, the anesthetic contained in the first breath is diluted by the lung volume. As the alveolar concentration increases, anesthetic is taken up faster by the blood. The partition coefficient will determine the limits of how quickly anesthetic will be absorbed by the blood. If the agent is very soluble, arterial blood will take the agent away quickly and alveolar concentration will rise slowly and thus increase anesthetic induction time. If the anesthetic agent is one of low solubility, then the alveolar concentration will rise quickly to inspired concentration levels and decrease induction time.

Naturally, the greater the inspired concentration, the faster alveolar concentration will rise. Also, the greater the alveolar ventilation the greater the rise in alveolar anesthetic concentration. The more soluble agents will have a slower induction and slower emergence than the less soluble agents.

Because the blood gas partition coefficient values equate vapor concentrations between gas and blood phases, and because equilibrium is expected to occur, the systemic arterial blood anesthetic concentration (Ca) can be calculated from CA: CA = fMAC = ml of vapor/dl; Ca = CA x L B/G = fMAC x L B/G ml of vapor/dl (Lowe and Ernst:1981:33). The speed of induction, maintenance and rate of recovery from a particular anesthetic agent depends upon factors affecting its uptake and distribution. Wood and Wood (1983:244) discuss uptake and distribution in their book.

The goal of the anesthetist is to develop an appropriate partial pressure of anesthetic agent within the patient's brain and keeping it at that level. The uptake of anesthetic has four phases: transport of the inspired gas from the anesthetic machine into the circuit, the uptake from the circuit into the lungs, the uptake from lungs into the arterial blood and finally the uptake from blood by the brain and other tissues. Thus, concentration gradients are formed between the circuit, alveoli, arterial blood, and finally tissues.

The cardiac output (Q, ml/min.) also affects uptake in a similar way. The greater Q, the greater the uptake of anesthetic from the alveoli. If Q is reduced, the alveolar concentration will rise faster but less anesthetic is carried away by the arterial blood. Thus, induction time will be decreased with a rise in Q. Induction time will be lengthened by a decrease in Q, even though the alveolar concentration rises more quickly, because less

anesthetic is removed from the alveoli and delivered to the brain. (Wood and Wood:1983:254).

Tissue capacity, tissue solubility and tissue blood flow and the partial pressure difference between arterial blood and the tissues also affect the uptake of anesthetic. Tissue capacity equals tissue volume times tissue solubility. Tissue capacity affects uptake because it is the final reservoir for the anesthetic agent. If a tissue capacity is great as in body lipid, it will dissolve a great deal of anesthetic. However, if that tissue has a poor blood supply as in body lipid, its rate of uptake will be small. Therefore, organ capacity = fMAC x L B/G x L T/B x organ volume.

Anesthetic requirements are based on a model advanced by Lowe and Ernst (1982:60). He studied anesthetic uptake on an organ by organ basis and derived a whole body uptake by adding up the uptakes of the individual organs. Individual organ (e.g. brain) capacity for halothane can be calculated as follows: brain halothane capacity = CA x L B/G x L T/B x organ volume (dl). The capacity of the brain to hold halothone then would be about 1 13 ml.

The anesthetic arterial concentration and the cardiac output determine the rate at which tissues saturate with anesthetic. Their product, Ca Q, represents the amount of anesthetic delivered to tissues every minute: CA = fMAC , C_a = CA x L B/G = fMAC x L B/G, CaQ = fMAC x B/G x Q.

The goal of CCA, like other techniques using inhalational agents is to supply the amount of anesthetic gas and oxygen to fill the breathing circuit and the lungs, and to saturate the blood with the desired concentration. Then, oxygen and anesthetic gases or vapors are added to the system only in amounts sufficient to replace that which is removed from the blood by tissue uptake. Thus, in CCA, the volume and concentration of gases in the system are kept constant.

Lowe and Ernst (1981:121) discuss uptake and clearance. In open circuits, the uptake of anesthetic is dependent upon ventilation. The amount of vapor absorbed versus the amount exhausted can vary with tidal volume, respiratory rate, anatomic dead space, shunts and alveolar ventilation. Hyperventilation in high-flow systems accelerates the rate of rise in alveolar concentration because anesthetic vapor is delivered in excessive amounts. Increased depth results and less anesthetic vapor is exhausted. Proper administration of CCA demands a constant anesthetic alveolar concentration. Thus, for CCA the rate of uptake is dependent upon cardiac output and anesthetic blood solubility and is independent of ventilation.

The clearance of anesthetic agent is difficult to predict because the mixed venous blood concentration of agent decreases with every breath at an exponential rate. Recovery times with closed and open circuit systems are identical at equivalent depths and durations of anesthesia. The recovery time with CCA should be more predictable, since the total administered dose is known (Lowe and Ernst:1981:121).

Lowe and Ernst (1981:67) discuss the square root of time model. As was mentioned earlier, Lowe studied anesthetic uptake on an organ by organ basis and derived whole body anesthetic uptake by adding the uptakes by the various organs. He then plotted the uptake curve and found that whole body anesthetic uptake decreased linearly with the square root of time: Qan = whole body uptake in ml/min = $K/\sqrt{t}$. The rate of uptake of anesthetic agent is inversely proportional to the square root of time and is proportional to a factor K, which is dependent on MAC, blood gas partition coefficient, and cardiac output. The linear inverse relationship between whole body uptake and the square root of time implies that once the desired CA and Ca are achieved by primary dose of agent, the tissues will absorb the same amount

of vapor during each square root of time interval. In order for Ca to remain constant, a "unit dose" must be delivered between 0-1, 1-4, 4-9, 9-16, 16-25, 25-36 minutes etc. Each time interval increases by two minutes.

The amount of vapor being delivered to all perfused tissues in the body each minute is CaQ: CaQ = Ca x Q = fMAC x L B/G x Q. The total body cumulative dose at any time (t) is 2 CaQ x$\sqrt{t}$. The rate of uptake for the total body Qan at any time (t) is the minute arterial delivery divided by the square root of that time: Qan = CaQ x $T^{-1/2}$ = fMAC x L B/G x Q X $t^{-1/2}$ = CaQ/$\sqrt{t}$ ml/min.

Priming is discussed by Lowe and Ernst (1981:58). The successful use of CCA requires that the pop-off valve remain closed and that total flows be adjusted to maintain a constant circuit volume. To rapidly attain a desired alveolar and arterial anesthetic concentration, an initial amount of anesthetic must be introduced into the circuit. The desired concentration will depend on the agent used. For example, to provide a 1.3 MAC of halothane is about 1% (1.3 x .75% = 1%).

The amount of anesthetic needed to prime the ventilatory component is the product of the system's volume times the desired alveolar concentration. The system volume (Vvent) is the sum of the circuit volume (Vcirc) plus the patient's functional residual capacity (FRC). For most adults Vvent = 100 dl: Ventilatory prime = Vvent x desired alveolar concentration = Vvent x CA = Vvent x fMAC, ventilatory prime = 100fMAC.

The amount of anesthetic required to prime the arterial component is the product of the desired concentration times the amount of blood circulating through the lungs during the first minute of anesthesia, or cardiac output Q: Arterial prime = desired concentration x Q = fMAC x L B/G x Q = CaQ.

The arterial prime (CaQ) represents the ml of vapor needed to fill the arterial delivery system with the desired concentration. That is, the amount of agent presented to all tissues per minute. The sum of the arterial and ventilatory prime is called the prime dose or that amount of agent to attain Ca: Prime dose = arterial prime + ventilatory prime, prime dose = CaQ + Vvent x fMAC = CaQ + 100 fMAC for the usual adult.

The prime dose is introduced once during the anesthetic, and Ca is kept constant by delivering into the circuit the amount of agent taken up by all of the tissues of the body. For example, the prime dose required by a 70 kg patient receiving isoflurane is (where F = 1.3, MAC = 1.3, Vvent = 100 dl and Q = $2kg^{3/4}$ or 48.4): Prime dose = CaQ + 100 fMAC = FMAC x L B/G x Q + 100 fMAC = 1.3 x 1.3 x 1.40 x 48.4 + 100 x 1.3 x 1.3 = 283.5 ml isoflurane vapor.

At a constant Ca, the body organs will accumulate anesthetic vapor predictably. The amount of isoflurane vapor being presented to body tissues each minute is the arterial concentration times the cardiac output or the minute arterial circulating amount (CaQ): CaQ = Ca x Q = fMAC x L B/G x Q = 1.3 x 1.3 x 1.4 x 48.4 = 114.5 ml of isoflurane vapor/minute.

The cumulative dose at anytime (t) is an amount equal to twice the minute arterial delivery multiplied by the square root of time: Cumulative dose = 2 CaQ x $t^{1/2}$ = 2 x fMAC x L B/G x Q $t^{1/2}$ = 2 CaQ x$\sqrt{t}$ ml of vapor.

The amount of vapor absorbed during the first minute, the (unit dose), is the same amount absorbed during each sequential square root of time interval: Cumulative dose at 1 minute = 2 CaQ x $1^{1/2}$ = 2 CaQ x$\sqrt{1}$, unit dose = 2 CaQ. (See Table 3).

Chapter 3

PROCEDURES

The procedures to perform this investigation involved library research. The resources necessary to complete these procedures were available.

A computer title search at Fairview Riverside Library was implemented. The University of Minnesota Biomedical Library and Hennepin County Medical Library were also utilized to perform library searches. Anesthesia journals and texts were used as references for the investigation of establishing a protocol for CCA. Tables and an illustration were utilized to demonstrate collected research data. No original data were collected in this investigation.

Chapter 4

RESULTS

The information found in the literature was used to develop a protocol for conducting CCA. Most of this information precedes the protocol. The definitions necessary to understand the protocol are found in Table 1. The procedure for calculating CCA dosages is found in table 2. Table 3 contains the necessary calculations for using inhalational agents in a closed-circuit. Table 4 contains the protocol for conducting CCA. A table of reference data may be found in Appendix A, table 5. Appendix B contains a drawing of an apparatus for the injection of liquid anesthetic into the circuit.

Table 1
Definitions pertinent to the understanding of CCA.

Abbreviation	Definition
Ca	arterial anesthetic concentration (ml vapor/ml, = CA X L B/G
CA	alveolar anesthetic concentration (ml vapor/ml) = fMAC
CaQ	amount of anesthetic vapor delivered to tissues in one minute, the minute arterial delivery: CaQ = fMAC x L B/G x Q
FRC	functional residual capacity is 2.5-3.5 liters in adults
f	fraction or multiple

Table 1 (continued)

L B/G - blood gas partition coefficient

L t - tissue blood partition coefficient

MAC - Minimum alveolar concentration required to suppress movement in 50% of patients undergoing surgical stimulation

1.3 MAC - minimum alveolar concentration required to suppress movement in 95% of patients undergoing surgical stimulation

prime dose - amount of gas or vapor needed to prime delivery system to desired concentration in (ml vapor)

Q - cardiac output = 2 $kg^{3/4}$ (ml/minute)

Qan - anesthetic uptake rate Qan = $CaQ\sqrt{t}$ ml of vapor/minute

QAN - total anesthetic uptake = 2 $CaQX\sqrt{t}$

Q t - tissue blood flow (ml/min)

t - time

unit dose - anesthetic tissue uptake during each time interval (ml of vapor)

VA - minute alveolar ventilation (ml/min)

VO^2 - metabolic oxygen consumption equals $kg^{3/4}$ x 1.6 oxygen consumption. VO^2 = 10 $kg^{3/4}$ at 37.6 c (ml/min)

VCO^2 - metabolic carbon dioxide production = 0.8 VO^2 or 8 $kg^{3/4}$. (ml/min)

V t - tissue volume

Vvent - volume of ventilatory delivery system (ml); usually 6-7 liters

Vcirc - volume of circuit; usually 3-4 liters

Table 2

Procedure for calculating closed-circuit anesthesia dosages.*

Prime Dose:	Unit Dose:
prime dose = CaQ = Vvent x fMAC	CaQ = fMAC x L B/G x Q unit dose = 2 CaQ

*
If more than one agent is used, f for each agent is determined so that the sum will equal 1.3 MAC. The calculations for unit and prime dose are performed for each agent. This information must be used to conduct CCA as outlined in the Protocol, pages 21 - 22.

Table 3

Sample calculations for inhalational agents

Agent	Calculation
Halothane summary - 100 kg patient, 1.3 MAC	
minute arterial delivery = CaQ = fMAC x L B/G x Q = 1.3 x 0.75 x 2.4 x 63.25	
CaQ = 148 ml of vapor/minute	
Qan = CaQ $t^{-1/2}$ = $148/\sqrt{t}$ ml of vapor/min	
cummulative dose = 2 CaQ $t^{1/2}$ = 296 $x\sqrt{t}$ ml of vapor	
unit dose = 2 CaQ = 296 ml of vapor	
prime dose = CaQ = 100 fMAC = 148 + 100(1.3 x 0.75) = 246 ml of vapor	
Enflurane Summary - 100 kg patient, 1.3 MAC	
minute arterial delivery = CaQ = fMAC x L B/G x Q = 1.3 x 1.7 x 1.9 x 63.25	
CaQ = 265.6 ml of vapor/minute	
Qan = CaQ $t^{-1/2}$ = $265.6/\sqrt{t}$ ml of vapor/minute	
cummulative dose = 2 CaQ $t^{-1/2}$ = 531 $x\sqrt{t}$ ml of vapor	
unit dose = 2 CaQ = 531 ml of vapor	
prime dose = CaQ = 100 fMAC = 265.6 = 100(1.3 x 1.7) = 487 ml of vapor	
Isoflurane Summary - 100 kg patient, 1.3 MAC	
minute arterial delivery = CaQ = FMAC x L B/G x Q = 1.3 x 1.3 x 1.5 x 63.25	
CaQ = 160.3 ml of vapor/minute	
Qan = CaQ $t^{-1/2}$ = $160.3/\sqrt{t}$ ml of vapor/min.	
cummulative dose = 2 CaQ $t^{1/2}$ = 321 $x\sqrt{t}$ ml of vapor	
unit dose = 2 CaQ = 321 ml of vapor	
prime dose = CaQ + 100 f MAC = 160 + 100(1.3 x 1.3) = 329 ml of vapor	

Lowe and Ernst (1981:67-87); calculations such as these are necessary to conduct CCA as outlined in the following protocal pages 21- 22 .

Table 3 (continued)

Nitrous Oxide Summary:

The unit dose of nitrous oxide is only 70% of the unit dose predicted by the square root of time model. Unit dose = 2 CaQ = 2(fMAC x L B/G x Q) = 2(65 x .46 x 63.25) = 3,782 ml of gas. The explanation is that the heart and kidney are saturated in 2 minutes which results in a left to right shunt that increase the rate of rise of venous concentration. This reduces the rate of uptake to 70% of predicted. Therefore, the equations are multiplied by 0.7 to correct the resulting volume.

Nitrous Oxide Summary - 100 kg patient, 1.3 MAC
minute anterial delivery = CaQ = fMAC x L B/G x Q = 65 x 0.46 x 63.25
CaQ = 1,891 ml of gas/minute
Qan = 0.7 x CaQ = $^{-1/2}$ = $1{,}324/\sqrt{t}$ ml of gas/min
cummulative dose 0.7 x 2 CaQ $t^{1/2}$ = $2{,}648\ x\sqrt{t}$ ml of gas
unit dose = 0.7 x 2 CaQ = 2,648 ml of gas
prime dose = CaQ + 100 fMAC = 1,891 + 6,500 = 8,391 ml of gas

Table 4

Protocol for conducting CCA.

EQUIPMENT

Anesthesia Machine
- low flow capability
- baralyme circle absorber
- polyethylene tubing
- check system for leaks

Oxygen Monitor
- sensor is placed in expiratory limb
- calibrate to room air and 100% oxygen
- set low alarm for oxygen % < 30
- check batteries

Ventilators
- use upright ascending bellows ventilator
- check for leaks

Anesthetic Agent Syringe (See Appendix B, Figure 1)
- connect a disposable 5 ml syringe to a teflon stopcock and attach to 21 gauge mental needle
- insert syringe into expiratory limb of anesthetic circuit or use a metal t-piece and syringe
- keep stopcock off when not injecting
- keep syringe horizontal
- avoid contact of liquid anesthetic with plastic
- do not place agent syringe on back table

Vaporizor
- must be accurate at flows less than 200 ml/min
- must be flow compensated

Table 4 (continued)

INDUCTION OF CCA

Preinduction and Induction

denitrogenate patient for 3 to 5 minutes with 100% oxygen and 6-10 liter flows

perform appropriate induction such as thiopental and succinylcholine and intubate patient

after intubation, reduce oxygen flow to the calculated metabolic value

close system by shutting pop-off valve

if nitrous oxide is used, fill system until oxygen is 30-40% of total

circuit volumes and oxygen % determine nitrous oxide flows, which will be constantly decreasing

dosage schedules are consulted secondarily for nitrous oxide

Administration of Volatile Anesthetic Agent

concurrently with adding nitrous oxide, give the primary dose and first unit of anesthetic - timer may be useful at this point

give a unit dose at each of the following minutes: 1, 4, 9, 16, 25, 36, 49, 64...

give an extra unit dose before incision

turn on after circuit is primed with nitrous oxide

Maintenance

oxygen and nitrous oxide flows are adjusted to yield constant oxygen concentration

system should be flushed with high flows for 5-10 minutes every two to three hours at 2L/min oxygen, 4L/nitrous oxide

if circuit seal is broken, use high flows for 5 minutes

if ventilator is used for ventilation, maintain bellows so that it never fully inflates

Table 4 (continued)

Emergence

omit administration of unit dose prior to expected completion of surgery

open system about 5 minutes before surgery is completed at 100% oxygen

Chapter 5

DISCUSSION, IMPLICATIONS AND RECOMMENDATIONS

An anesthetic machine for the conduction of closed-circuit anesthesia must have low-flow capability. That is, the rotameters must be capable of delivering precise flows over a range of 10 ml/min to 10,000 ml/minute. It is possible to use the meters with low-flow capability or an empty copper-kettle if flowmeters are otherwise unavailable (Lowe and Ernst:1981:154).

It is important to use baralyme and not soda lime with halothane as the agent. Halothane reacts with soda lime producing CF2 CBr CL which is known to be toxic to mice and can accumulate in closed-circuits (Mostert:1979:2). Furthermore, baralyme does not absorb volatile anesthetics. Polyethylene anesthetic tubing is preferable to rubber tubing because it absorbs less anesthetic agent (O'leary:1979:5). Because, carbon dioxide absorbent is so important to CCA, it is critical to check the dye incidator before every case.

Oxygen monitors are another critical component of CCA, and their function must be checked with every case. The sensor is placed in the expiratory limb of the circuit because that is the place one would more likely record a low reading. An even better arrangement would be to have an oxygen monitor on both the inspiratory and expiratory limb providing better monitoring and a check on the monitors themselves.

When ventilators are used, it is essential to use one with upright ascending bellows. If a leak develops it is easily discovered, since the

bellows will collapse. Inverted bellows are difficult to detect leaks. Do not let the bellows fully inflate, in order to insure an accurate volume.

Anesthetic can be delivered into the system by vaporizer, direct injection or a metal T-piece with syringe attached. (See Appendix B, Figure 1.) When using a syringe, use disposable polyethylene syringe and a metal needle. Anesthetic liquid will melt the plastic hub of disposable needles. Also keep the syringe horizontal on the T-piece to prevent accidental injection of agent. Another safety recomendation, is never keep agent filled syringes on your back table or it may be accidentally injected into the patient.

Some vaporizors are not accurate at delivering anesthetic at low flows or are subject to unacceptable variation. Lin (1980:354) in his study of vaporizer performance in closed-circuits, discovered that all vaporizers were acceptably accurate except the Fluotec Mark II. He also discovered that any vaporizer can be affected by nitrous oxide output and positive pressure ventilation. He recommends that oxygen flushing be abandoned in conducting closed-circuit anesthesia, or flushed with the vaporizer off.

Although doses for nitrous oxide are calculated, its flows are determined by circuit volume and oxygen concentration. Denitrogenation is important since one would like to use oxygen and nitrous oxide in the system. Eighty precent of the FRC is nitrogen in an adult, or about 2000 ml. A study by Barton and Nunn (1975:350) found that after flushing, nitrogen increased by only 4% in one hour. Diluted in a 10 liter Vvent, this quantity is insignificant. It is unlikely that nitrogen will increase to 10%.

If the seal is broken on a closed-circuit, nitrogen will enter the circuit. Flushing with high flows for five minutes and re-sealing the circuit will effectively remove the nitrogen (Lowe and Ernst:1981:12). Anytime there is

a problem in the conduct of CCA, the practitioner can always revert to a semi-closed high flow system. Thus, the conduct of CCA can be made safe even with the attentive novice.

The reward for practicing CCA is the ability to constantly measure oxygen consumption, the variation of which reflects changes in cardiac output, depth of anesthesia, body temperature and other metabolic disturbances. However, since CCA deals quantitatively with all factors influencing the delivery of general anesthesia, a certain exposure to mathematics is essential. The reliance on equations to deliver general anesthesia can be cumbersome until facility is attained.

The square root of time model is an example of an exact formula developed to approximate the variables upon which conduct of general anesthesia rests. The practioner must always give anesthetic according to what the patient needs and not necessarily according to the calculated dose. Many factors control the variable elements from which formulas are derived. These variable elements such as age, weight, % of body fat,and temperature etc. can make calculations only an approximation. Therefore, calculations provide a working base in CCA, but the patient determines the specific doses given.

Few anesthesia machines in the Twin Cities are capable of delivering the precise flows required by CCA. Most have been built with high flows in mind. Leaking machings, which can be easily accomodated by high flow techniques, are not suitable for CCA. The adoption of CCA techniques would certainly lead to an upgrade in the performance and manufacture of anesthesia machines.

A protocol is available for anesthetists to follow, and the calculations have been simple enough to expedite the process. Therefore, it is recommended that CCA anesthesia be studied and practiced. The protocol provides a method whereby the anesthetist, with proper equipment, can conduct an excellent CCA. It is recommended that CCA be practiced on any case where high flows have been used in the past, even pediatrics (Couto da Silva et. al. 1984:765). The only restriction is the motivation of the anesthetist.

Variations in the conduct of CCA are also available. Gorsky et. al. (1978:18) tested Lowe's square-root-of-time-model with mass spectrometry and found the calculations an excellent place to start. However, he found that anesthetic concentrations were not accurately predicted. He therefore recommends a compromise system that uses high flows initially and then close the circuit some minutes later, taking advantage of both semi-closed and closed techniques.

The potential for positive change, that is, a wider practice of CCA, probably depends more upon the availability of proper equipment then the initiative of the anesthetist. Nevertheless, if anesthetists adopt this style of anesthesia there are cost savings and ecological advantages. In fact, CCA will likely be the technique of the hour, should anesthetists ever be required to purchase their own anesthetics.

In summary, CCA is a suitable and practical method of conducting a general anesthetic. It deserves to have a wider acceptance because of its many advantages--advantages of better monitoring, economy of cost and ecology. CCA's disadvantages are not significant with an attentive practitioner.

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APPENDIX A

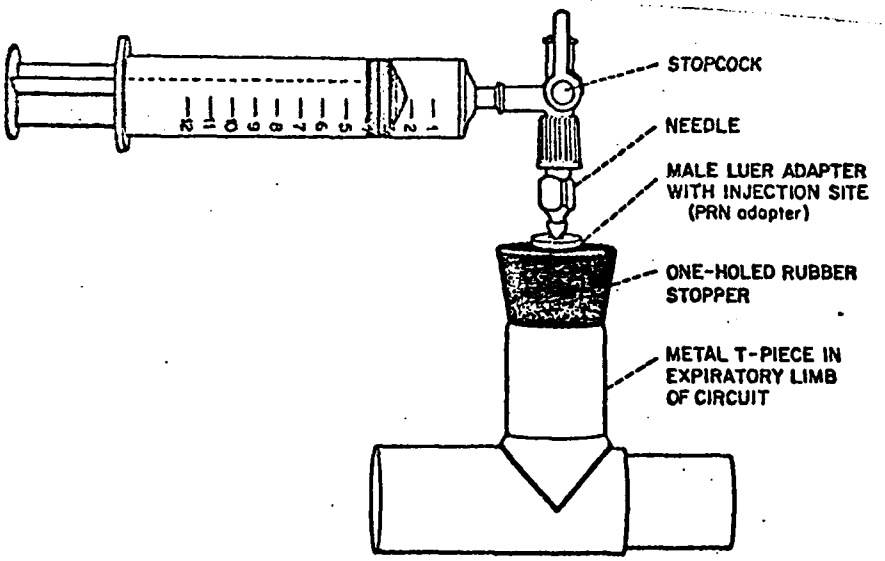
TABLE 5

MAC, LB/G*, and ML of Vapor per ML of Liquid Values
for Inhalational Anesthetics
(Lebowitz et.al. 1982:470)

GAS	MAC	LB/G	ML of Vapor per ML of Liquid
Halothane	0.76	2.3	240
Enflurane	1.7	1.90	210
Isoflurane	1.3	1.48	206
Nitrous Oxide	101	0.47	___

*Blood gas partition coefficient or Ostwald solubility coefficient.

APPENDIX B



Apparatus for Injection of Liquid Anesthetic
into a Closed Anesthetic Circuit
(Lebowitz, et.al. 1982:468)